

**Abstract.** A homogeneous set of  $UBV$  photometry (354 data points obtained between 1983 and 1998) for the Be/X-ray binary A0535+26 = V725 Tau is analysed, aiming to look for possible periodic component(s). After subtraction of the long-term variation it was found that only a  $\approx 103^d$  periodic component remains in the power spectra in both the  $V$  and  $B$  colour bands. The probability of chance occurrence of such a peak is less than 0.1%. There are no signs of optical variability at the X-ray period ( $\approx 111^d$ ). We discuss possible reasons for a 103-day modulation and suggest that it corresponds to a beat frequency of the orbital period of the neutron star and the precession period ( $\approx 1400^d$ ) either of an accretion disc around the neutron star or a warped decretion disc around the Be star.

**Key words:** stars: binaries: general – stars: circumstellar matter – stars: individual: V725 Tau – stars: pulsars: individual: A0535+26 – stars: variables: general – accretion, accretion discs

# X-ray and optical periodicities in X-ray binaries. I. A0535+26

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## 1. Introduction

The X-ray binary A0535+26 has been an object of interest to both observers and theorists for a quarter of a century, from the moment of its first documented X-ray outburst in 1975 (Rosenberg et al. 1975). As soon as an optical counterpart was identified almost simultaneously by several authors (Liller 1975; Murdin 1975) with the 9th magnitude Be star HDE 245770, later named V725 Tau, there were several attempts to find the orbital period of the system, using both X-ray and optical (spectral and photometric) data.

Priedhorsky & Terrell (1983) have shown that all but the most powerful X-ray outbursts (1975 April and 1980 October) take place with a period  $\approx 111$  days. Now the general opinion is that the orbital period is 110–111<sup>d</sup>. The most reliable determination of the X-ray period and initial epoch is currently that of Motch et al. (1991):  $P_{\text{XR}} = 111^{\text{d}}38 \pm 0^{\text{d}}11$  and  $T_0 = \text{JD}2446734.3 \pm 2^{\text{d}}6$ .

This and other periodicities were claimed to have been found in optical (photometric and spectral) data. For instance, Hutchings et al. (1978) found that the radial velocities of absorption lines of HDE 245770 are variable, and suggested several probable periods: 28.6, 48 and 94 days. Some years later and based on a very similar dataset, Hutchings (1984) found a 112 day period. Guarnieri et al. (1982) noted at first possible 32, 63 or 77 day periods in their photometric data, but later (Guarnieri et al. 1985) found modulation in the *V* band photometry with the proposed orbital period of 110 days. Gnedin et al. (1988) made a Fourier analysis of *V* band photometry obtained during 1981–1985 and marked out periods of 1100, 103 and 28 days, but found no periodicity corresponding to the X-ray period.

Besides the determinations noted above, there are several more publications on this subject, listed by Giovannelli and Graziati (1992).

In a recent paper by Hao et al. (1996) all the published data sets from 1981 to 1993 have been analysed together. Their analysis have shown only two significant periods –

830 and 507 days. However their light curve modeling does not agree with the observational data and their prognosis of the photometric behavior of HDE 245570 for 1994–1997 was not confirmed by later observations (see Fig. 1 in Hao et al. 1996, Fig. 1 in Lyuty & Zaitseva 2000 and Fig. 2 in this work). It should be noted also that in Hao et al. (1996) no correction has been made for different zero-points and colour systems of the data sampled by different groups.

As soon as our data set had grown substantially and surpassed that used in Gnedin et al. (1988), as well as other published data sets, we attempted to search for periodic components in the light curves of A0535+26/V725 Tau. In Sect. 2 we describe our techniques of data analysis and obtain a value of the optical period, distinctly different from the orbital one, while in Sect. 3 we discuss possible reasons of the light modulation and suggest that it is caused by interplay of the orbital and precession motions. In Sect. 4 we summarize the results.

## 2. An analysis of optical data

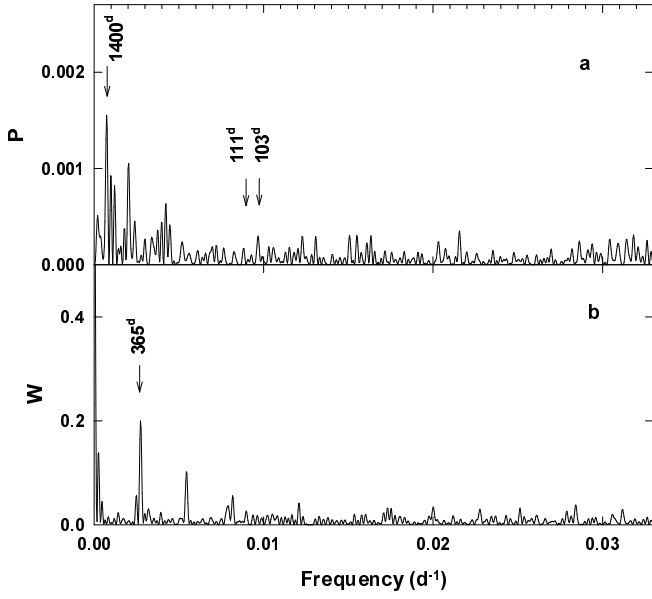
All the photometric data discussed herein have been obtained in the period 1983–1998 with a photon-counting photometer at the 60 cm telescope of the GAISH Crimean laboratory (for details see Lyuty & Zaitseva 2000). More than 350 individual *UBV* measurements have been made; the photometric accuracy is 0<sup>m</sup>.005 in *B*, *V* and 0<sup>m</sup>.008 in *U*. As the long-term behavior of V725 Tau has been discussed in separate papers (Clark et al. 1999, Lyuty & Zaitseva 2000), we restrict ourselves here only to the analysis of variability on the time scales close to the X-ray period.

We calculate the power spectrum and spectral window of the data set as

$$P(f) = \frac{1}{N^2} \left| \sum_{j=1}^N (m_j - \bar{m}) e^{-i2\pi f t_j} \right|^2 \quad (1)$$

and

$$W(f) = \frac{1}{N^2} \left| \sum_{j=1}^N e^{-i2\pi f t_j} \right|^2, \quad W(0) = 1, \quad (2)$$



**Fig. 1.** **a** Power spectrum and **b** spectral window in the  $V$  band for our 1983–1998 observations after subtraction of the linear trend. The highest peak corresponds to a (quasi)period of  $\approx 1400^{\text{d}}$ .

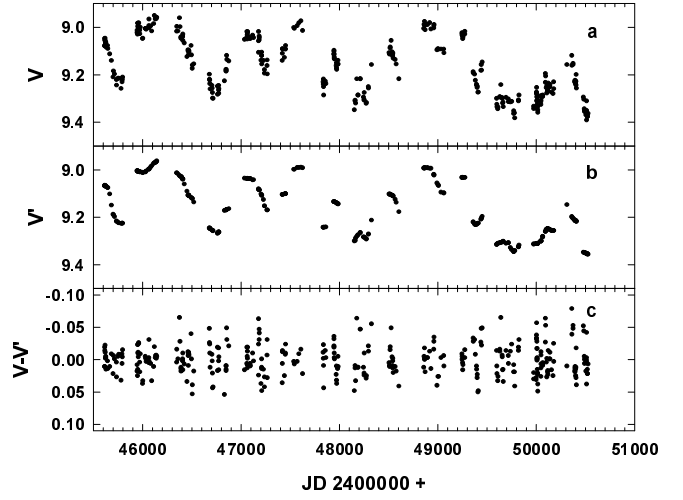
respectively, where  $i = \sqrt{-1}$ ,  $t_j$  denotes the time of observation, and  $m_j$  and  $\bar{m}$ , correspondingly, the individual and mean values of the brightness.

Fig. 1a shows the power spectrum of the  $V$  band data (linear trend removed) for the period from 1983 to 1998. The largest peak in the spectrum corresponds to  $\approx 1400$  days and is readily explainable: a wave with that characteristic time scale is easily seen in Fig. 2, superimposed on a smooth decay in brightness, in the optical and infrared light curves (see also Larionov 1993 and Clark et al. 1999). In the region of the orbital period ( $\sim 0.01 \text{ d}^{-1}$ ), only a faint peak corresponding to  $P = 103^{\text{d}}$  is seen. At the frequency corresponding to a 111 day period, there is no peak at all.

In order to judge with sufficient confidence the reality of the orbital plus close and/or related periodicities, one should remove the longer-period component(s) of variability. In our case it is not sufficient to subtract the linear trend, and we need to take into account the slow light variations with a (quasi)period of  $\approx 1400$  days. We have constructed an approximating data set using the method of a sliding mean with the window value  $\Delta$ , replacing raw data  $m_i$  for each time  $t_i$  by the weighted mean:

$$m'_i = -2.5 \log \left( \frac{1}{\sum p_j} \sum_{j=1}^k p_j \cdot 10^{-0.4m_j} \right), \quad (3)$$

where  $k$  is the number of data points within interval  $[t_i - \Delta, t_i + \Delta]$ , and the weight of  $j$ th point is determined as  $p_j = \exp [-(\delta t_j / \Delta)^2]$ ,

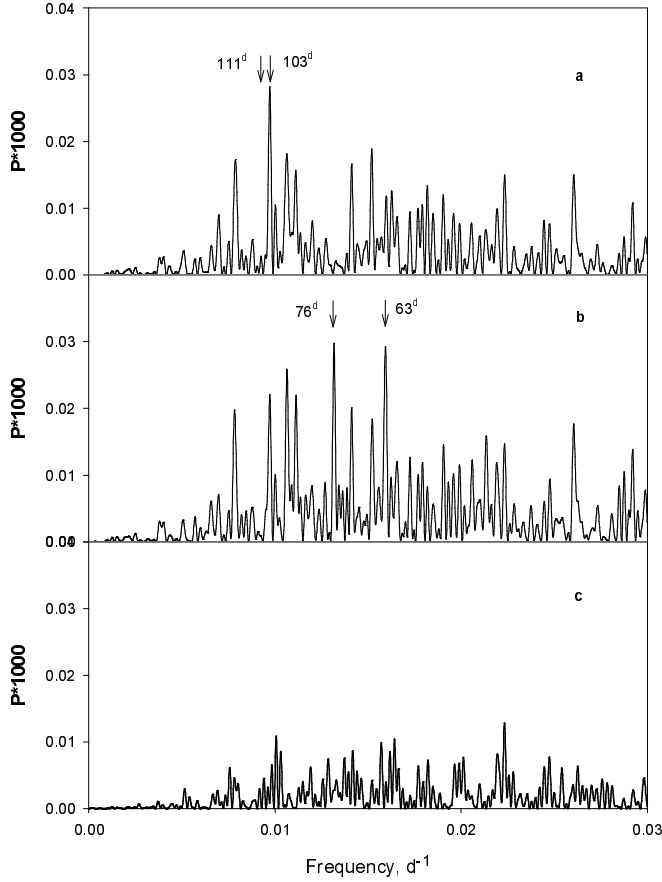


**Fig. 2.** **a** The light curve of V725 Tau in  $V$  band, **b** smoothed light curve with a  $50^{\text{d}}$  window, and **c** residuals after subtraction of the smoothed curve.

where  $\delta t_j$  is the time span from the  $j$ th point to the center of the window. The optimal value of the smoothing interval was searched by trial and error within a range  $20^{\text{d}} < \Delta < 100^{\text{d}}$ . The criterion for  $\Delta$  selection was the signal-to-noise ratio of the power-spectrum peaks in the region of interest, i.e. around the orbital frequency. The raw and smoothed light curves, and also the residuals between them, are plotted in Fig. 2. The power spectrum for the residuals  $m_j - m'_j$  is shown in Fig. 3. We have found that, independent of the value of the smoothing interval adopted, the most prominent peak in the power spectrum corresponds to a period of  $102^{\text{d}}83 \pm 0^{\text{d}}1$ , while the low-frequency components are most effectively suppressed and the highest signal-to-noise ratio is obtained when  $\Delta = 50^{\text{d}}$ . We have obtained an analogous result for the  $B$  band as well.

The amplitude of the sine-wave obtained is  $0^{\text{m}}015$  in  $V$  and  $0^{\text{m}}01$  in  $B$ , while in  $U$  the 103-day peak is not seen above the noise. The significance of the detection of the faint sine-wave superimposed on the large-amplitude slow variability can be tested by adding an artificial low-amplitude harmonic to the raw data. We added a sine-wave with  $P = 76^{\text{d}}$  and amplitude  $0^{\text{m}}015$  to the raw  $V$  data, then repeated the same cleaning routine as described above (Eqs. 3 and 4). Fig. 3 demonstrates that the low-frequency filtration method described above can be used to detect, *at least for the data set discussed*, periodic variability on a time scale of  $\sim 100^{\text{d}}$  with amplitude  $\geq 0^{\text{m}}01$ .

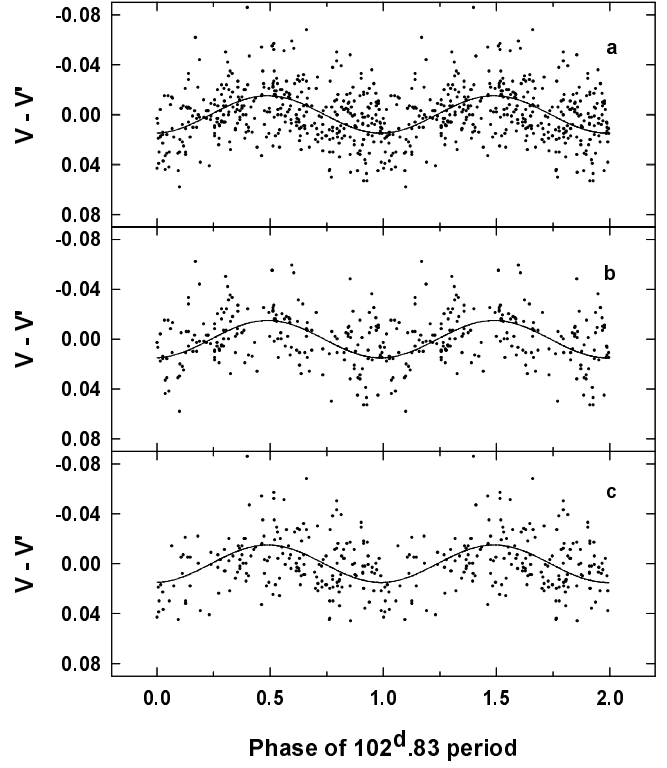
In order to test whether the 103-day period is real or an artifact intrinsic to some part of the data set, we have split the initial data set into two parts corresponding to values above and below the linear trend and have repeated the same procedure. We have found that the 103-day harmonic is intrinsic to both parts of the initial dataset, although for the low-brightness part the significance of the



**Fig. 3.** **a** Power spectrum of the residuals  $V - V'$  on our 1983–1998 data. The most prominent peak corresponds to  $P = 102^{\text{d}}.92$ . **b** To check the efficiency of smoothing, an artificial sine-wave with  $P = 76^{\text{d}}$  amplitude  $0^{\text{m}}.015$  was added. Additional peaks in the spectrum, the most prominent of which are at  $P = 63^{\text{d}}$ , are caused by aliasing of the  $P = 76^{\text{d}}$  period with the peaks in the spectral window. The slight decrease in the power of  $P = 102^{\text{d}}.83$  peak, as compared to the upper panel, is caused by a redistribution of power as a result of the cleaning process on our non-uniformly spaced data set. **c** Power spectrum after subtraction of  $102^{\text{d}}.83$  and  $91^{\text{d}}.07$  period sine-waves from the initial light curve.

$103^{\text{d}}$  peak is slightly less. Fig. 4 gives the phase curves of residuals  $V - V'$  for the whole data set and for the “upper” and “lower” parts of it. It is easily seen that both the shape and initial phases are the same. We calculate the ephemeris of the small-scale optical variations as  $JD_{\text{Min}} = 2448002(\pm 3^{\text{d}}.0) + 102^{\text{d}}.83(\pm 0^{\text{d}}.15) \cdot E$ , where  $E$  is the epoch number.

The probability of chance occurrence of a peak with amplitude  $P_{\text{max}}$  in the power spectrum with a mean value  $P_{\text{mean}}$  can be estimated as  $\Phi = 100\% \cdot \{1 - [1 - \exp(-(P_{\text{max}}/P_{\text{mean}}))]^{N_{\text{ind}}}\}$ ; for non-uniformly spaced data the number of independent frequencies  $N_{\text{ind}} = -6.362 + 1.193 \cdot N + 0.00098 \cdot N^2$ , where  $N$  is the number of obser-



**Fig. 4.** **a**  $V - V'$  dependence on the phase of the  $103$ -day period for the whole set of data, **b** for the “upper” and **c** for the “lower” part of it. A  $0^{\text{m}}.015$  sine-wave is superimposed on each panel.

vations (Horne and Baliunas 1986). In our case  $N = 354$  and  $N_{\text{ind}} = 539$ ; after subtraction of the slow component as described above (Eqs. 3 and 4),  $\Phi < 0.1\%$ .

Nevertheless, there are some peaks in the frequency range  $0.007 - 0.017$  with power  $> 10^{-5}$ . In order to test their reality, we have followed the recipe given by Horne and Baliunas (1986) for irregularly spaced data and subtracted a  $103^{\text{d}}$  period sine-wave from the initial light curve. After this we find that only a peak at a frequency corresponding to  $91^{\text{d}}.07$  and its aliases remain in the power spectrum. This feature replaces the  $103^{\text{d}}$  periodicity from  $JD\ 2449400$  (1993 April) onwards. It is remarkable that this change of periods coincides with the time of the most prominent X-ray outburst over the past three decades.

Fig. 3c displays power spectrum after subtraction of a sine-wave of period  $103^{\text{d}}$  before 1993 April and  $91^{\text{d}}$  after that time. Comparing Fig. 3a and Fig. 3c, we conclude that only the  $103^{\text{d}}$  and  $91^{\text{d}}$  peaks are real, although the latter feature is present in only 1/5 of the total data set, thus preventing us from making exact estimates of the ephemeris. A slight enhancement of the noise level around  $0.01\ \text{d}^{-1}$  on Fig. 3c is most probably caused by the deviation of the real signal from a true sine-wave.

### 3. Discussion

We stress once again that the 111-day orbital periodicity is not revealed in the optical photometry. It is then natural to suppose that one of the constituents of the total radiation of the system, besides that of the optical star, is that of a precessing disc – either an accretion disc around the neutron star or a tilted/warped equatorial envelope around the optical star. The period of precession, whichever precessing body, would then be  $P_{\text{prec}} = 1/(1/P_{\text{opt}} - 1/P_{\text{x-ray}}) = 1360^{\text{d}} \pm 30^{\text{d}}$ , and  $\sim 900^{\text{d}}$  after 1993 April. In the following we consider these two scenarios separately.

#### 3.1. Accretion disc

In the case of the neutron star (NS) accretion disc, the axis of the disc is inclined to the orbital plane of the system and, additionally, is counter-precessing with a  $\approx 1360^{\text{d}}$  period. In this case the disc cross-section, as seen from the optical companion, would be changing with a frequency equal to the sum of orbital and precession frequencies, which would lead to the 103-day modulation observed.

The existence of an accretion disc in this binary system at least during some X-ray outbursts is firmly established – it is confirmed by quasi-periodic oscillations of X-rays during X-ray outbursts (Finger et al. 1996, 1996) and by neutron star spin-up episodes (Nagase et al. 1984). However, the question as to whether the disc exists permanently or is formed just before the outburst remains unresolved.

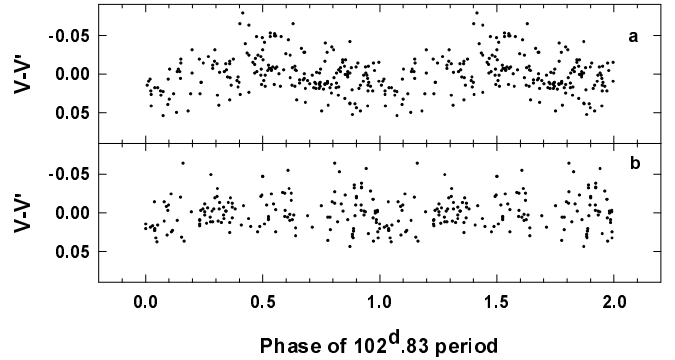
A similar model was proposed to describe the optical light curves of some other X-ray binaries: Cen X-3, LMC X-4 and others (see, e.g., Heemskerk & van Paradijs 1989) – however, unlike A0535+26, these systems show orbital variability besides precession. This can be explained by the fact that A0535+26 is a wide binary, and the effects caused by the ellipsoidal shape of the optical component and/or its X-ray heating are unobservable. Also, in the case of A0535+26 the large eccentricity of the orbit –  $e \approx 0.5$  (Finger et al. 1994, 1996) – plays a major role. As a result, both the effective cross-section of the disc to the stellar wind and its illumination in periastron and apastron would differ by  $\sim 9$  times; when  $\approx 1360$  day precession is added, this enables the 103-days modulation to be observed.

Meanwhile, the disc’s input to the total optical radiation of the system can be as small as a few per cent (Lyuty & Zaitseva 2000), and it would be quite a difficult task to distinguish it based on the difference between its photometric and/or spectral parameters and those of a giant star and its envelope.

The disc is not expected to rotate as a solid body, and its structure is dependent on X-ray outbursts occurring at the surface of the neutron star and subsequent re-radiation of stored energy. Because of this, neither the amplitude of

precession modulation nor the period and phase of precession should be stable.

Meanwhile, we see that during the first 10 years of our observations (up to 1993), the 103-day periodicity of the optical variations is retained, which means that the precession period is rather stable, changing from  $\sim 1360^{\text{d}}$  to  $\sim 900^{\text{d}}$  after the major X-ray outburst. Nevertheless, as expected, in the total radiation of the system the relative contribution of the component connected with the disc precession is not constant. Fig. 5 illustrates the phase curves in  $V$  band after subtraction of the slow component, separately for the ascending and descending branches of the initial light curve shown in Fig. 2. It is evident that the 103-day modulation is practically absent when the light level is increasing, and, on the contrary, is quite distinct when the light fades.



**Fig. 5.**  $V - V'$  dependence on the phase of the 103-day period **a** for descending and **b** ascending branches of the slow component of the light curve (see Fig. 2).

One of the possible mechanisms of stimulation of the accretion disc precession is free precession of the neutron star. It was shown by Schwarzenberg-Czerny (1992) that  $P_{\text{pr}}/P_{\text{spin}} \approx 10^6$ , where  $P_{\text{pr}}$  is the period of free precession of a neutron star and  $P_{\text{spin}}$  is the period of its axial rotation. In the case of A0535+26  $P_{\text{spin}} \approx 104^{\text{s}}$  and correspondingly  $P_{\text{pr}} \approx 1200^{\text{d}}$ . It is natural to suppose that the proximity of this period to the characteristic time of the large-scale photometric variability is not coincidental. What then can serve as a “transmission link” from the freely precessing neutron star and its accretion disc to the equatorial envelope of the optical component? Let us be reminded that the neutron star in A0535+26 system has a powerful magnetic field,  $\approx 10^{13}$  G. Periodic changes in orientation of the magnetic field relative to the equatorial envelope would lead to periodic changes in the strength of their interaction, first of all near periastron; the shock wave arising in the envelope would lead to (quasi)periodic ejections of the envelope. Clark et al. (1999) and Lyuty & Zaitseva (2000) argue that the long time scale variability of A0535+26 in the period we are analysing is explained by the successive expulsions of the Be star envelope that

occur on a characteristic time-scale of  $\approx 1400$  days. We have to note, however, that the detailed description of the interaction of the Be star envelope and NS magnetic field needs additional modelling work that is beyond the scope of this paper.

### 3.2. Be-star equatorial envelope

A quite different approach may be considered on the basis of recent analysis of spectral variability of another Be/X-ray binary, V635 Cas=4U0115+63, made by Negueruela and Okazaki (2001) and Negueruela et al. (2001). These authors argue that in V635 Cas, just as in similar Be/X-ray systems, a major role is played by an equatorial decretion disc around the optical star. This disc is truncated as a result of tidal/resonant interaction with the neutron star companion. At a certain stage the disc becomes unstable, tilts and warps and starts to precess. Later on, the disc is disrupted due to interaction with the orbiting neutron star, and a giant X-ray outburst may occur. The above authors argue that this model does not imply any substantial change in the optical star's mass loss rate.

Following that idea, we may suppose that the precessing body in the A0535+26 system is a tilted/warped disc around Be star. Then it is natural that the gravitational pull of the neutron star in the moments of closest approach of the NS to the disc causes its distortion, which is observed in the light curve as minor variations superposed on global changes. Due to precession, the times of closest approach do not coincide with the periastron passages, but rather precede them by  $\approx 8^{\text{d}}$  after each orbit. Within this approach we can find a natural explanation for the fact that during the ascending parts of the global light curve, no 103-day modulation is seen: it only means that the decretion disc is not large enough to become tilted and warped and therefore it does not precess.

To further develop this model, one may speculate that the changes of projection of the warped disc to the plane of sky, as seen from the optical companion, should cause substantial variations with the precessional period, superposed on the optical light curve. This is actually observed: we noted before the coincidence of the 1400<sup>d</sup> time-scale of global optical variations with almost the same period of precession – whichever the precessing body.

One might expect that the X-ray activity within the system may also in some way be connected with the phases of the 103<sup>d</sup> period. We tried to check whether such a correlation exists, and found that out of 18 documented outbursts with amplitude  $\geq 0.2$  Crab (Giovannelli & Graziati, 1992 and Finger et al. 1996), 7 peaked in a narrow interval 0.6 – 0.7 of the optical phase curve (Figs. 4 and 5), where phase 0.0 refers to optical minimum (see Table 1). This means that X-ray outbursts “prefer” to happen 10 to 20 days after the optical maxima. If we consider this in the context of the warped decretion disc model, this delay can be explained as the time needed for the matter captured

JD2400000+	X-ray flux (Crab units)	$\Phi_{102.8^{\text{d}}}$
42533	2.8	0.81
42614	0.2	0.60
42724	0.3	0.67
42829	0.3	0.69
43288	0.5	0.15
43508	0.5	0.29
43617	0.2	0.35
43732	0.7	0.47
43951	0.2	0.60
44522	1.5	0.15
44952	0.2	0.33
45290	0.2	0.62
45515	0.5	0.81
45619	0.8	0.82
45732	0.8	0.92
46736	0.8	0.68
47625	0.6	0.33
49403	1.4	0.62

**Table 1.** Julian dates, X-ray fluxes and optical phases of the outbursts with  $F(2 - 10)\text{keV} \geq 0.2$  Crab. X-ray data are from Giovannelli & Graziati (1992) and Finger et al. (1996). Giant outbursts of 1975 and 1980 are included.

from the Be-star disc – disturbed during the close passage of the neutron star – to travel to the vicinity of the NS companion, where it loses its angular momentum, falls onto the NS, and causes an X-ray flare. It can be noted that during 2001 two occasions of favourable X-ray and optical phases will be in June and October; unluckily, the former date corresponds to the seasonal gap of observations.

## 4. Conclusion

An analysis of the uniform photometric data set obtained in the period 1983–1998 has allowed a confident separation of the periodic constituent in the light curve of the high-mass X-ray binary, A0535+26/V725 Tau. The parameters of this periodic component and its link with the phase of activity of the optical component allow us to suggest precession of an accretion disc around the neutron star or a warped equatorial disc around a Be star as the most likely mechanisms. At this point, both models seem to be viable; meanwhile, the analysis of already existing spectral data could be helpful, in the sense that if the warped disc model does reflect reality, one might expect to see  $V/R$  and  $EW$  variations corresponding to the precessional motion.

Within both models, we do not expect that substantial X-ray outbursts to occur during ascending parts of the large-scale optical light curve. Moreover, X-ray outbursts tend to occur at specific phases of the 102<sup>d</sup>8 optical light curve. Taken together, both effects can explain the “missing outburst” phenomenon.

Our results lead us to suppose that in other similar systems we can hope to distinguish the minor photometric variations close to, but not necessarily coincident with, the binary rotation period. In future papers of this series, we plan to apply the techniques described here to the analysis of the light curves of similar systems, such as X Per and V635 Cas.

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